

# NLO EW corrections to $pp \rightarrow WW \rightarrow 4l$ in double-pole approximation at the LHC

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in collaboration with S. Dittmaier, B. Jäger and C. Speckner

based on JHEP 1312 (2013) 043 [[arXiv:1310.1564 \[hep-ph\]](https://arxiv.org/abs/1310.1564)]

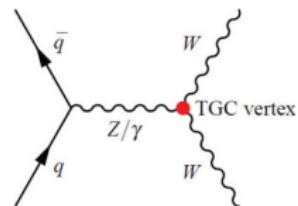
Fermilab  
2 July 2014

# Motivation

## $W^+W^-$ production at the LHC

- probe non-abelian structure of the Standard Model

- ▶ measurement of anomalous gauge couplings



## Four lepton production at the LHC

- background process for

- ▶  $H \rightarrow WW^* \rightarrow 4l$
- ▶ new physics searches with leptons +  $\cancel{E}_T$  signatures  
(e.g. SUSY-particle pair production)

→ we need precise theoretical SM predictions:

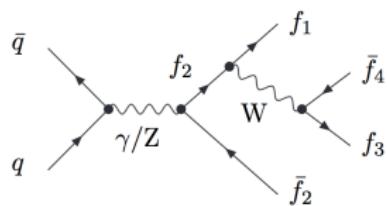
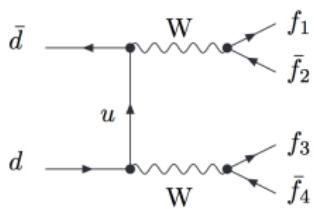
NLO QCD, NNLO QCD, NLO EW (+ parton shower matching)



*NLO QCD*

# NLO QCD

- ⊕  $h_1 h_2 \rightarrow W^+ W^-$ : [Ohnemus '91; Frixione '93]
- ⊕ including leptonic decays and singly resonant contributions:
  - ▶ analytical expressions:  
[Dixon, Kunszt, Signer '98; Baur, Han, Ohnemus '96]
  - ▶ implementation in public code MCFM and phenomenological studies:  
[Campbell, Ellis, Williams '99; '11]



# NLO QCD

$$pp \rightarrow W^+ (\rightarrow e^+ \nu_e) W^- (\rightarrow \mu^- \bar{\nu}_\mu)$$

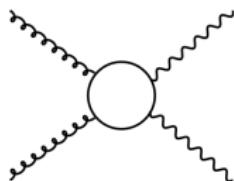
no jet veto applied!

$\sqrt{s}$ [TeV] and cuts	$\sigma^{LO}(e^+ \mu^- \nu_e \bar{\nu}_\mu)$ [fb]	$\sigma^{NLO}(e^+ \mu^- \nu_e \bar{\nu}_\mu)$ [fb]	K-factor	% gg
7 (Basic)	144	249	1.73	3.05
7 (Higgs)	7.14	15.19	2.13	6.85
14 (Basic)	296	566	1.91	4.73
14 (Higgs)	13.7	34.7	2.53	10.09

table taken from [Campbell, Ellis, Williams '11]

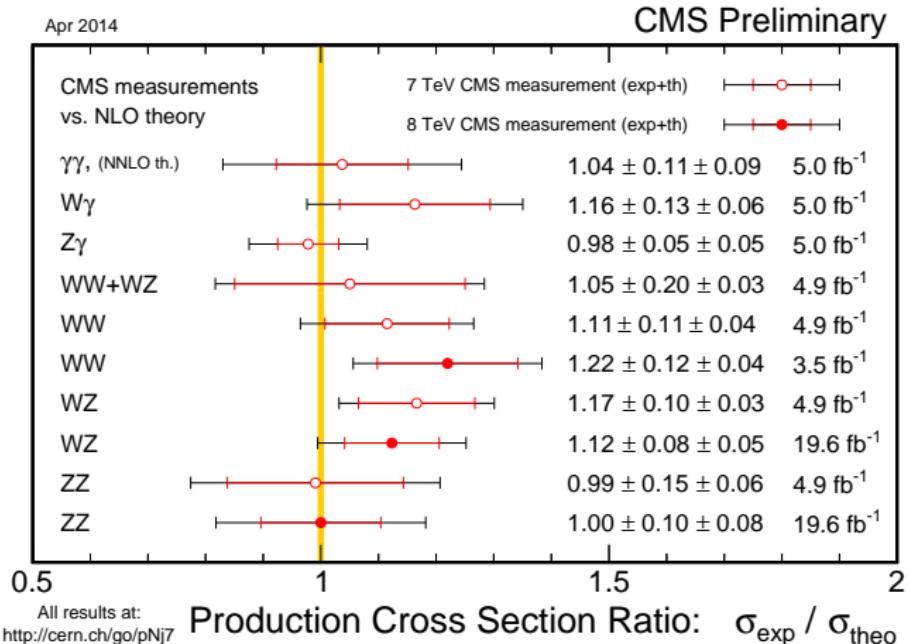
- size of NLO-QCD corrections is large and cut-dependent
- not expected from variation of central scale  $M_W/2 \leq \mu_f \leq 2M_W$  at LO (qg channels)

# loop-induced gluon–gluon contribution



- ⌚ considered first by [Dicus, Kao, Repko '87; Glover, van der Bij '89]
- ⌚ phenomenological study for the LHC:  
[Dührssen, Jakobs, van der Bij, Marquard '05]
- ⌚ inclusion of off-shell effects and heavy-quark loops:  
[Binoth, Ciccolini, Kauer, Krämer '05, '06; Binoth, Kauer, Mertsch '08]
- impact of gg contribution is strongly cut dependent
- not negligible (especially for LHC running at 14 TeV)

# Experimental results: CMS



# Data vs SM prediction

Cross section measurement of W-pair production			
LHC	7 TeV	ATLAS	$\sigma_{\text{exp}} = 51.9 \pm 2.0(\text{stat}) \pm 3.9(\text{syst}) \pm 2.0(\text{lumi}) \text{ pb}$
		MCFM	$\sigma_{\text{theo}} = 44.7 \pm 2.0$
	CMS		$\sigma_{\text{exp}} = 52.4 \pm 2.0(\text{stat}) \pm 4.5(\text{syst}) \pm 1.2(\text{lumi}) \text{ pb}$
		MCFM	$\sigma_{\text{theo}} = 47.0 \pm 2.0$
	8 TeV	ATLAS	?
		CMS	$\sigma_{\text{exp}} = 69.9 \pm 2.8(\text{stat}) \pm 5.6(\text{syst}) \pm 3.1(\text{lumi}) \text{ pb}$
		MCFM	$\sigma_{\text{theo}} = 57.3 \pm 2.0 \text{ pb}$
Tevatron	1.96 TeV	CDF	$\sigma_{\text{exp}} = 14.0 \pm 0.6(\text{stat})^{+1.6}_{-1.3}(\text{syst}) \pm 0.8(\text{lumi}) \text{ pb}$
		MC@NLO	$\sigma_{\text{theo}} = 11.7 \pm 0.9 \text{ pb}$

→ slightly larger cross sections measured compared to SM predictions  
missing NNLO QCD ???



*NNLO QCD*

# NNLO QCD

Impressive progress in the last years

- ④  $\gamma\gamma$  ✓ [Catani, Cieri, de Florian, Ferrera, Grazzini '11]
- ④  $Z\gamma$  ✓ [Grazzini, Kallweit, Rathlev, Torre '13]
- ④  $W\gamma$  **preliminary results** presented at LoopFest XIII

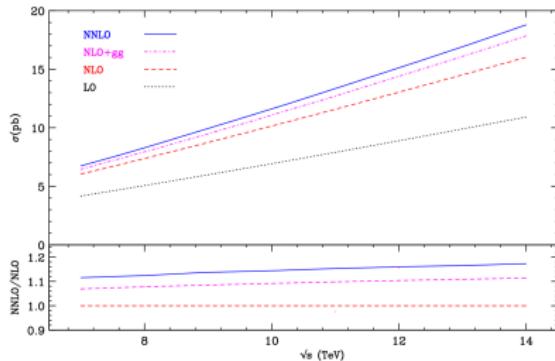
		LO	NLO	NNLO	exp.
$W^+$	$\sigma$ [pb]	0.511(1)	1.155(1)	1.371(5)	
	rel. correction		126%	19%	
$W^-$	$\sigma$ [pb]	0.395(1)	0.910(1)	1.085(4)	
	rel. correction		130%	19%	
total	$\sigma$ [pb]	0.906(1)	2.065(1)	<b>2.456(6)</b>	2.770(340)
	rel. correction		128%	19%	

table taken from talk by Dirk Rathlev

# NNLO QCD

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- ⌚  $Z\gamma$  ✓ [Grazzini, Kallweit, Rathlev, Torre '13]
- ⌚  $W\gamma$  preliminary results presented at LoopFest XIII
- ⌚  $ZZ$  (✓) [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, v. Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]



- ⌚  $WZ$  X
- ⌚  $WW$  X

# steps towards NNLO QCD corrections to WW

- ⌚ [Chachamis, Czakon, Eiras '08]  
numerical results only valid in high energy limit
- ⌚ [Campanario, Rauch, Sapeta '13] using the LoopSim method:  
combine NLO-QCD samples for WW and WW $j$
- ⌚ [Dawson, Lewis, Zeng '13]  
combination of NLO QCD calculation  
with soft-gluon resummation of threshold logs

$\sigma(\text{pb})$	$\sqrt{S} = 7 \text{ TeV}$	$\sqrt{S} = 8 \text{ TeV}$	$\sqrt{S} = 13 \text{ TeV}$	$\sqrt{S}=14 \text{ TeV}$
$\sigma^{NLO}$	$45.7_{-1.1}^{+1.5}$	$55.7_{-1.2}^{+1.7}$	$110.6_{-1.6}^{+2.5}$	$122.2_{-1.8}^{+2.5}$
$\sigma^{gg}$	$1.0_{-0.2}^{+0.3}$	$1.3_{-0.3}^{+0.4}$	$3.5_{-0.7}^{+0.9}$	$4.1_{-0.7}^{+0.9}$
$\sigma^{NLO+NNLL}$	$44.9_{-0.6}^{+0.6}$	$54.8_{-0.8}^{+0.7}$	$108.2_{-1.5}^{+1.3}$	$119.5_{-1.6}^{+1.5}$
$\sigma'^{NLO+NNLL}$	$45.9_{-0.6}^{+0.5}$	$56.1_{-0.8}^{+0.7}$	$111.7_{-1.6}^{+1.8}$	$123.6_{-1.8}^{+2.0}$
$\sigma_{approx}^{NNLO}$	$45.0_{-0.1}^{+0.4}$	$54.9_{-0.05}^{+0.5}$	$108.3_{-0.4}^{+1.0}$	$119.6_{-0.5}^{+1.2}$
$\sigma_{approx}^{NNNLO}$	$46.0_{-0.047}^{+0.4}$	$56.2_{-0.1}^{+0.6}$	$111.8_{-1.1}^{+1.7}$	$123.7_{-1.2}^{+1.8}$

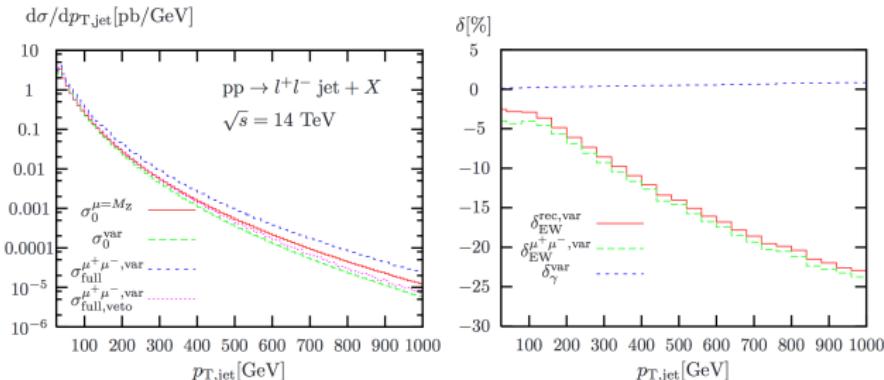
table taken from [Dawson, Lewis, Zeng '13]



*NLO EW*

# EW corrections – really important?

- generic size:  $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \rightarrow \text{NNLO QCD} \sim \text{NLO EW}$
- systematic enhancements
  - Sudakov logarithms  $\alpha \ln^2(M_Z/Q)$  and subleading logs at high scales  $Q$  ( $\rightarrow$  New Physics)

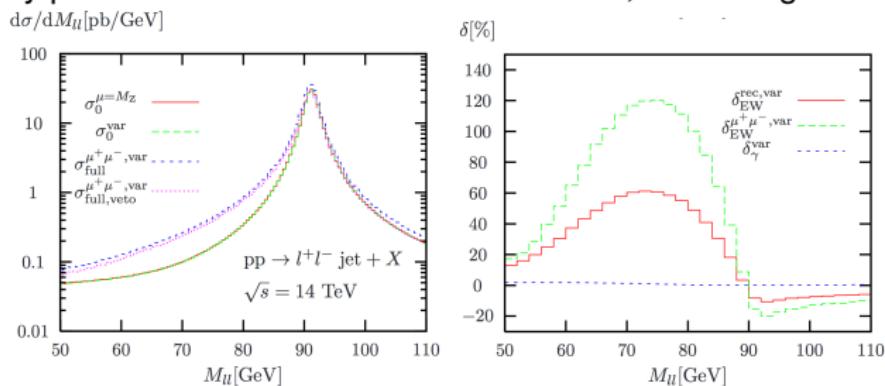


dilepton + jet production at the LHC

[Denner, Dittmaier, Kasprzik, Mück '11]

# EW corrections – really important?

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  - by photon emission  $\rightarrow$  kinematical effects, mass-singular log's



dilepton + jet production at the LHC

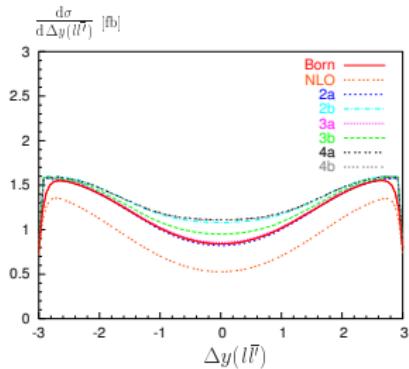
[Denner, Dittmaier, Kasprzik, Mück '11]

# Known results – logarithmic approximations

## EW corrections – logarithmic approximations

⌚ [Accomando, Denner, Kaiser 05/06]

- ▶ retain only universal logarithms that are large at high energies
- ▶ double-pole approximation for W bosons
- ▶ unknown EW corrections can fake anomalous triple-gauge boson couplings



[Accomando, Kaiser '05]

⌚ [Kühn, Metzler, Penin, Uccirati '11]

- ▶ one- and two-loop electroweak corrections in next-to-next-to-leading logarithmic approximation in high-energy limit

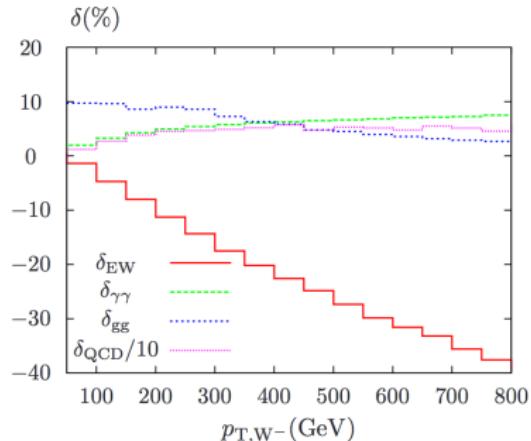
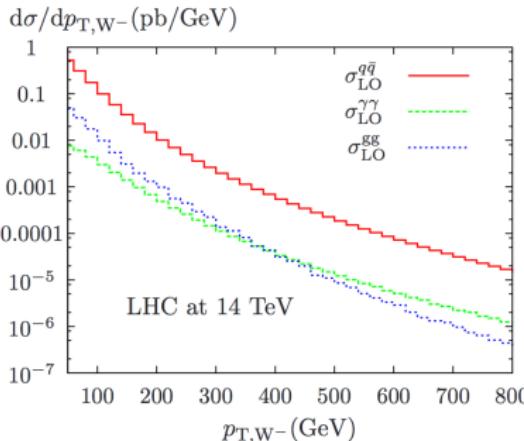
# Existing results – fixed order calculations

## Fixed order calculations including EW corrections

- one-loop corrections to on-shell  $W^+W^-$  production

[Bierweiler, Kasprzik, Kühn, Uccirati '12/13]

- one-loop corrections to on-shell  $W^+W^-$  production including  $\gamma q$ -induced contributions [Baglio, Ninh, Weber '13]



[Bierweiler, Kasprzik, Kühn, Uccirati '12]

# Existing results – fixed order calculations

## Fixed order calculations including EW corrections

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- ⌚ one-loop corrections to on-shell  $W^+W^-$  production including  $\gamma q$ -induced contributions [Baglio, Ninh, Weber '13]
- EW corrections for integrated cross sections:  $\mathcal{O}(1\%)$
- EW corrections for distribution at high scales: up to **-40%**

## Purpose of our calculation

- ⌚ inclusion of off-shell effects
- ⌚ inclusion of final-state radiation off charged leptons
- ⌚ reasonably fast code compared to full calculation
  - employ approximations

# Our calculation: RacoonWW approach

RacoonWW:  $e^+e^- \rightarrow 4$  fermions in double-pole approximation

[Denner, Dittmaier, Roth, Wackerlohe '00]

## Leading order

- full off-shell calculation of  $pp \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e$

## NLO EW corrections

### Virtual corrections:

$\sqrt{\hat{s}} > 2M_W + x$ : Double-pole approximation (DPA)

→ corrections to doubly resonant diagrams only

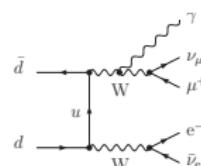
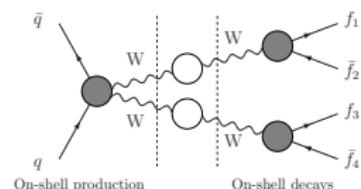
$\sqrt{\hat{s}} < 2M_W + x$ : Improved Born approximation (IBA)

[Denner, Dittmaier, Roth, Wackerlohe '01]

### Real corrections:

full off-shell calculation (including final state radiation)

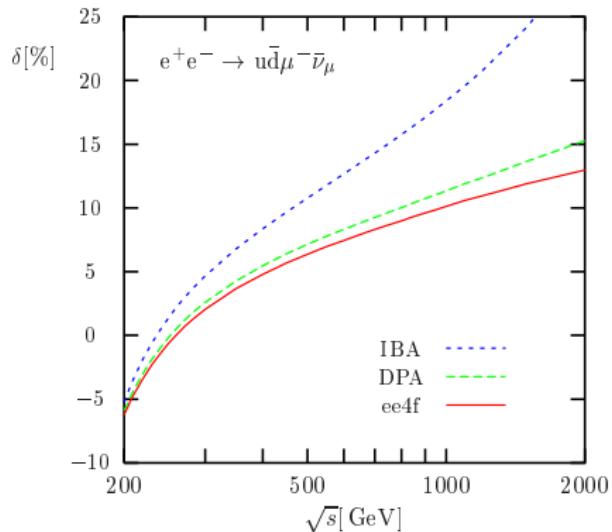
- full information on photon momentum



# Remark : Validity check of DPA

Comparison of RacoonWW result to full off-shell calculation of  $e^+e^- \rightarrow 4f$

- error estimate of less than few % confirmed at moderate scales
- $\sim 5\%$  discrepancy at 2 TeV



[Denner, Dittmaier, Roth, Wieders '06]

# Our calculation: Different contributions

Leading order: full off-shell calculation

- $\bar{q}q$ -induced contribution ( $q = u, d, c, s$ )

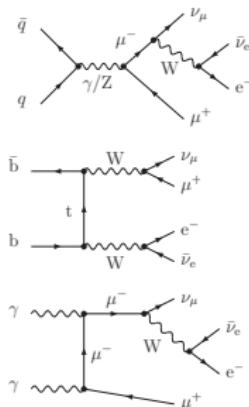
$$\bar{q}q \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e$$

- $\bar{b}b$ -induced contribution (< 2% @LO)

$$\bar{b}b \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e$$

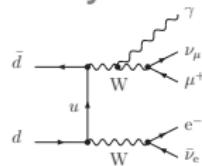
- $\gamma\gamma$ -induced contribution (< 1% @LO)  
(uncertainty on photon pdfs huge!)

$$\gamma\gamma \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e$$



EW corrections to  $\bar{q}q$ -induced contribution only

- **Virtual** corrections: IBA / DPA
- **Real** corrections: full off-shell calculation

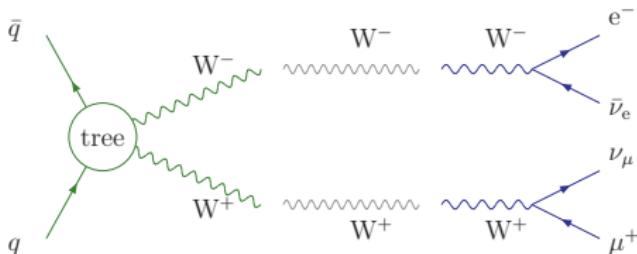




*Double-pole approximation – basic idea*

# Double-Pole Approximation

LO



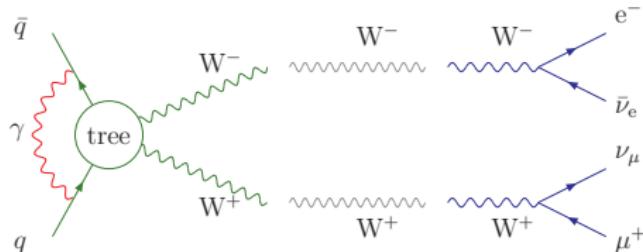
on-shell production   Breit-Wigner   on-shell decay

$$\begin{aligned}\mathcal{M}_{\text{Born}, \text{DPA}} &= \sum_{\lambda_+, \lambda_-} \frac{1}{[k_+^2 - M_W^2 + iM_W\Gamma_W] [k_-^2 - M_W^2 + iM_W\Gamma_W]} \\ &\times \left\{ \mathcal{M}_{\text{Born}}^{\bar{q}q \rightarrow W^+ W^-} \mathcal{M}_{\text{Born}}^{W^+ \rightarrow \nu_\mu \mu^+} \mathcal{M}_{\text{Born}}^{W^- \rightarrow e^- \bar{\nu}_e} \right\}\end{aligned}$$

- ⌚ consider on-shell production of  $W$  pair and on-shell  $W$  decay
- ⌚ add off-shell propagators including Breit-Wigner distribution
- ⌚ sum over the polarization states
- ⌚ for gauge invariance: on-shell projection of momenta needed!
- ⌚ error estimate:  $\Gamma_W/M_W$

# Double-Pole Approximation

NLO

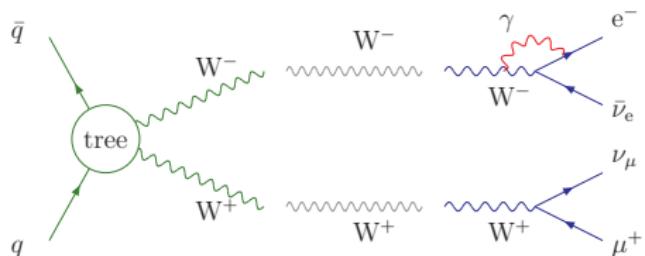


on-shell production    Breit-Wigner    on-shell decay

One distinguishes between **factorizable** (corrections to the decay OR to the production) and non-factorizable corrections (only soft photon exchange).

# Double-Pole Approximation

NLO

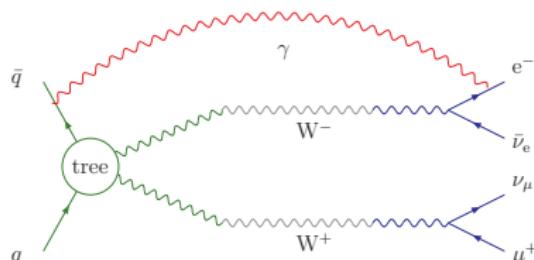


on-shell production    Breit-Wigner    on-shell decay

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# Double-Pole Approximation

NLO



One distinguishes between factorizable (corrections to the decay OR to the production) and **non-factorizable** corrections (only soft photon exchange).

- (selection of all doubly resonant one-loop diagrams to  $\text{pp} \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e$ )
- (expansion around the poles)
- (error estimate:  $\alpha/\pi \times \Gamma_W/M_W$ )

## Advantages

- (# diagrams reduced)
- (diagrams much easier to calculate (without DPA EW corrections to  $2 \rightarrow 4$  process!)  $\rightarrow$  **faster code**)

# Virtual corrections in DPA

$$\int_4 d\hat{\sigma}_{\bar{q}q}^{\text{virt,DPA}} \sim \int_4 d\Phi_4 \left\{ 2 \operatorname{Re} \left[ \left( \mathcal{M}_{\text{Born,DPA}}^{\bar{q}q \rightarrow WW \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e} \right)^* \delta \mathcal{M}_{\text{virt,fact,DPA}}^{\bar{q}q \rightarrow WW \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e} \right] + \left| \mathcal{M}_{\text{Born,DPA}}^{\bar{q}q \rightarrow WW \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e} \right|^2 \delta_{\text{nfact}}^{\text{virt}} \right\}$$

## Factorizable Corrections

$$\delta \mathcal{M}_{\text{virt,fact,DPA}}^{\bar{q}q \rightarrow W^+ W^- \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e} = \sum_{\lambda_+, \lambda_-} \frac{1}{[k_+^2 - M_W^2 + iM_W\Gamma_W] [k_-^2 - M_W^2 + iM_W\Gamma_W]} \\ \times \left\{ \delta \mathcal{M}_{\text{Born}}^{\bar{q}q \rightarrow W^+ W^-} \mathcal{M}_{\text{Born}}^{W^+ \rightarrow \nu_\mu \mu^+} \mathcal{M}_{\text{Born}}^{W^- \rightarrow e^- \bar{\nu}_e} \right. \\ \left. + \mathcal{M}_{\text{Born}}^{\bar{q}q \rightarrow W^+ W^-} \delta \mathcal{M}_{\text{Born}}^{W^+ \rightarrow \nu_\mu \mu^+} \mathcal{M}_{\text{Born}}^{W^- \rightarrow e^- \bar{\nu}_e} \right. \\ \left. + \mathcal{M}_{\text{Born}}^{\bar{q}q \rightarrow W^+ W^-} \mathcal{M}_{\text{Born}}^{W^+ \rightarrow \nu_\mu \mu^+} \delta \mathcal{M}_{\text{Born}}^{W^- \rightarrow e^- \bar{\nu}_e} \right\}$$

## Non-factorizable corrections

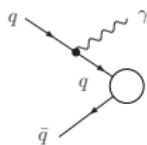
- finite part: very small (for  $e^+ e^- \rightarrow 4f$ ) [Denner, Dittmaier, Roth '97]
- singular part: important for cancellation of IR singularities

# Real corrections: $\bar{q}q \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e \gamma$

## Subprocesses with final-state photon

- Dipole subtraction formalism [Dittmaier '99]

$$\int_5 d\hat{\sigma}_{\bar{q}q}^{\text{real}} + \int_0^1 dx \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{fact}} = \underbrace{\int_5 \left[ d\hat{\sigma}_{\bar{q}q}^{\text{real}} - d\hat{\sigma}_{\bar{q}q}^{\text{real,sing}} \right]}_{\text{IR finite}} + \int_4 \left[ \int_1 d\hat{\sigma}_{\bar{q}q}^{\text{real,sing}} \right] + \int_0^1 dx \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{fact}}$$



► Convolution part with collinear IS singularities absorbed into PDFs (Factorization)

► Endpoint contribution for cancellation of IR singularities in virtual corrections

# Cancellation of IR singularities

Soft and collinear singularities are regularized by introducing an infinitesimal photon mass  $\lambda$  and small fermion masses  $m_i$ .

(checked against pure dim. regularization)

→ cancellation between virtual and real corrections

## Endpoint contribution

$$\int_5 d\hat{\sigma}_{ab}^{\text{real,sing}} = \int_0^1 dx \int_4 d\hat{\sigma}_{ab}^{\text{real,conv}} + \int_4 d\hat{\sigma}_{ab}^{\text{real,endp}}$$

$$\int_4 d\hat{\sigma}_{\bar{q}q}^{\text{virt,fin}} = \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{virt}} + \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{real,endp}}$$

$$d\hat{\sigma}_{ab}^{\text{real,endp,DPA}} =$$

$$- d\hat{\sigma}_{ab}^{\text{Born,DPA}} \frac{\alpha}{2\pi} \sum_{i=1}^6 \sum_{j=i+1}^6 (-1)^{i+j} Q_i Q_j \left[ \mathcal{L}(\hat{\mathbf{s}}_{ij}, m_i^2) + \mathcal{L}(\hat{\mathbf{s}}_{ij}, m_j^2) + \text{const.} \right]$$

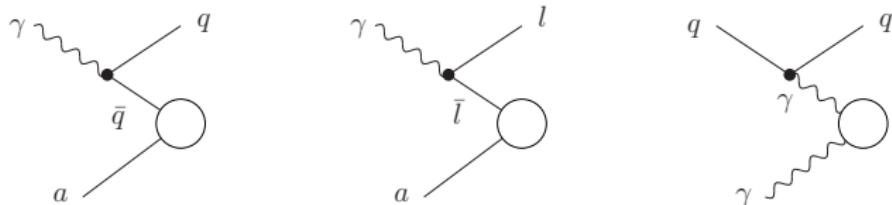
$$\mathcal{L}(s, m^2) = \ln\left(\frac{m^2}{s}\right) \ln\left(\frac{\lambda^2}{s}\right) + \ln\left(\frac{\lambda^2}{s}\right) - \frac{1}{2} \ln^2\left(\frac{m^2}{s}\right) + \frac{1}{2} \ln\left(\frac{m^2}{s}\right)$$

→ IR-finite!

# Real corrections: $\gamma q \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e q$

Photon-quark induced subprocesses  
no soft, only collinear singularities occur

- ④  $\gamma \rightarrow \bar{q}q$ : dipole subtraction
- ④  $\gamma \rightarrow \bar{l}l$ : cut on transverse momentum of charged leptons
- ④  $q \rightarrow \gamma^* q$ : effective collinear factor
  - restores regulator mass dependence in singular limit
  - mass dependence drops out by redefinition of pdfs



# Improved Born Approximation

[Denner, Dittmaier, Roth, Wackerlohe '01]

$$d\hat{\sigma}_{q\bar{q}}^{\text{IBA}} = F(x_1 x_2) d\Phi_4 \overline{\sum} \left| \mathcal{M}_{\text{IBA}}^{\bar{q}q \rightarrow \nu_\mu \mu^+ e^- \bar{\nu}_e} \right|^2 \left[ 1 + \delta_{\text{Coul}}(\hat{s}, k_+^2, k_-^2) \right] g(\bar{\beta})$$

- captures dominant universal parts of virtual corrections
- Coulomb singularity [Fadin et al., Beenakker et al.]:

$$\begin{aligned}\delta_{\text{Coul}}(\hat{s}, k_+^2, k_-^2) &= \frac{\alpha(0)}{\bar{\beta}} \text{Im} \left\{ \ln \left( \frac{\beta - \bar{\beta} + \Delta_M}{\beta + \bar{\beta} + \Delta_M} \right) \right\}, \\ \bar{\beta} &= \frac{\sqrt{\hat{s}^2 + k_+^4 + k_-^4 - 2\hat{s}k_+^2 - 2\hat{s}k_-^2 - 2k_+^2k_-^2}}{\hat{s}}, \\ \beta &= \sqrt{1 - \frac{4(M_W^2 - iM_W\Gamma_W)}{\hat{s}}}, \quad \Delta_M = \frac{|k_+^2 - k_-^2|}{\hat{s}}\end{aligned}$$

- damping factor:

$$g(\bar{\beta}) = (1 - \bar{\beta}^2)^2$$

# Further details on our calculation

## Details on the theoretical site

- Complex mass scheme [Denner, Dittmaier, Roth, Wieders '05]  
 $\mu_V^2 = M_V^2 - iM_V\Gamma_V$  for  $V = W, Z$ ,  $c_W = \mu_W/\mu_Z$
- photon recombination necessary (*dressed leptons*)
- EW scheme [Les Houches 2013: 1405.1067 [hep-ph]]
  - ▶  $\alpha_{G_\mu}$  for LO contribution  
accounts for higher order corrections associated with running coupling and universal top-mass corrections to  $\rho$  parameter
  - ▶  $\alpha_{G_\mu}$  for finite virtual corrections
  - ▶  $\alpha(0)$  for the coupling of an external photon

# Further details on our calculation

## Details on the technical site

- Matrix elements based on RacoonWW
- all LO MEs checked against Madgraph
- multi-channel integrator based on Coffery $\gamma\gamma$  for  $\gamma\gamma \rightarrow 4f$   
[Bredenstein, Dittmaier, Roth '05]
- Tools for virtuals: In general we use
  - ▶ FeynArts
  - ▶ inhouse Mathematica routines
  - ▶ Collier [Denner, Dittmaier, Hofer]  
→ Fortran code
- Setup for independent check only:
  - ▶ FeynArts, FormCalc, LoopTools [Hahn et al.]

# Our calculation: Summary

$$\begin{aligned}\sigma_{\text{pp}}^{\text{NLO}} &= \int_0^1 dx_1 \int_0^1 dx_2 \left\{ \left( \sum_{q=u,d,c,s} f_q(x_1, \mu_F) f_q(x_2, \mu_F) \right. \right. \\ &\quad \times \left[ \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{LO}} + \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{virt}} + \int_5 d\hat{\sigma}_{\bar{q}q}^{\text{real}} + \int_0^1 dx \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{fact}} \right] \\ &\quad \left. \left. + (q \leftrightarrow \bar{q}) \right) \rightarrow \delta_{\bar{q}q} \right.\end{aligned}$$

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&\quad \times \left[ \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{LO}} + \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{virt}} + \int_5 d\hat{\sigma}_{\bar{q}q}^{\text{real}} + \int_0^1 dx \int_4 d\hat{\sigma}_{\bar{q}q}^{\text{fact}} \right] + (q \leftrightarrow \bar{q}) \Bigg) \\
&\quad \rightarrow \delta_{\bar{q}q} \\
&\quad + f_\gamma(x_1, \mu_F) \sum_{q=u,d,c,s} \left( f_q(x_2, \mu_F) \left[ \int_5 d\hat{\sigma}_{\gamma q}^{\text{real}} + \int_0^1 dx \int_4 d\hat{\sigma}_{\gamma q}^{\text{fact}} \right] + (q \leftrightarrow \bar{q}) \right) \\
&\quad + f_\gamma(x_2, \mu_F) \sum_{q=u,d,c,s} \left( f_{\bar{q}}(x_1, \mu_F) \left[ \int_5 d\hat{\sigma}_{\bar{q}\gamma}^{\text{real}} + \int_0^1 dx \int_4 d\hat{\sigma}_{\bar{q}\gamma}^{\text{fact}} \right] + (\bar{q} \leftrightarrow q) \right) \\
&\quad \rightarrow \delta_{\gamma q} \\
&\quad + \left( f_b(x_1, \mu_F) f_b(x_2, \mu_F) \int_4 d\hat{\sigma}_{bb}^{\text{LO}} + (b \leftrightarrow \bar{b}) \right) \\
&\quad \rightarrow \delta_{bb} \\
&\quad \left. + f_\gamma(x_1, \mu_F) f_\gamma(x_2, \mu_F) \int_4 d\hat{\sigma}_{\gamma\gamma}^{\text{LO}} \right\} \\
&\quad \rightarrow \delta_{\gamma\gamma}
\end{aligned}$$

# Numerical Setup

## Default Setup

- NNPDF2.3qed
- factorization scale  $\mu_F = M_W$
- photon recombination

## Minimal Cuts

- $p_{T,\ell} > 20 \text{ GeV}, |y_\ell| < 2.5$
- jet veto:  $p_{T,\text{jet}} > 100 \text{ GeV}$

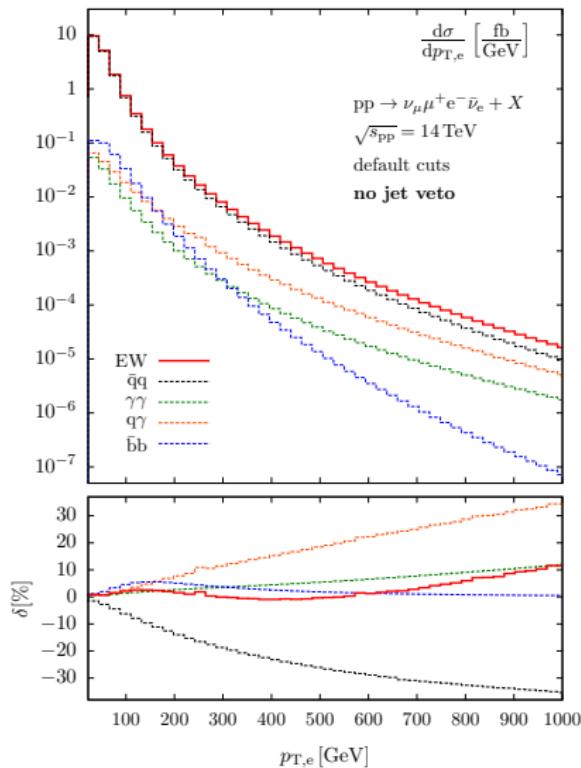
## ATLAS Cuts

- $p_{T,\ell} > 20 \text{ GeV}, |y_\ell| < 2.5$
- $p_{T,\ell}^{\text{leading}} > 25 \text{ GeV}, E_T^{\text{miss}} > 25 \text{ GeV}, R_{e\mu} > 0.1, M_{e\mu} > 10 \text{ GeV}$
- jet veto:  $p_{T,\text{jet}} > 25 \text{ GeV}$

	$\sigma_{\bar{q}q}^{\text{LO}} [\text{fb}]$	$\delta_{\bar{q}q} [\%]$	$\delta_{\gamma q} [\%]$	$\delta_{\gamma\gamma} [\%]$	$\delta_{\bar{b}b} [\%]$
LHC14	412.5	-2.7	0.6	0.7	1.7
LHC8	236.8	-2.8	0.5	0.8	0.9
ATLAS cuts	163.8	-3.0	-0.3	1.0	1.0

$\delta_x$ : relative correction by contribution x compared to  $\sigma_{\bar{q}q}^{\text{LO}}$

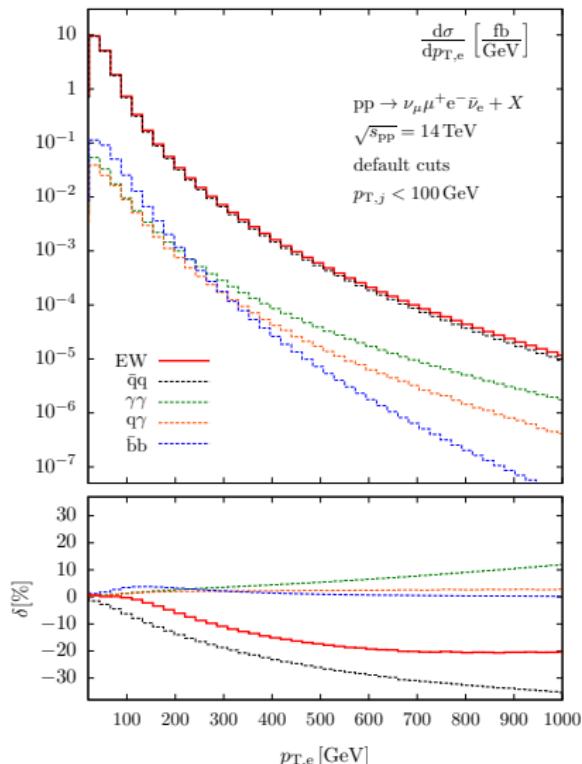
# LHC14: transverse momentum distribution



without jet veto

- \*  $\delta_{\bar{q}q}$ : -30% at  $p_T = 900 \text{ GeV}$   
(Sudakov logs)
- \*  $\delta_{\gamma\gamma}$ : up to +10%
- \*  $\delta_{q\gamma}$ : large due to **soft W emission**
  - same effect in QCD corrections
  - leads to huge  $K$ -factors
  - apply jet veto

# LHC14: transverse momentum distribution



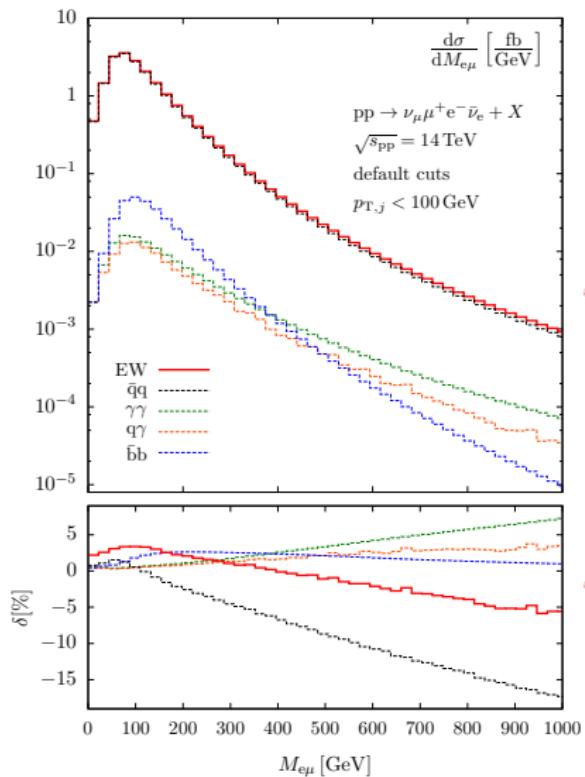
without jet veto

- \*  $\delta_{\bar{q}q}$ : -30% at  $p_T = 900 \text{ GeV}$   
(Sudakov logs)
- \*  $\delta_{\gamma\gamma}$ : up to +10%
- \*  $\delta_{q\gamma}$ : large due to **soft W emission**  
→ same effect in QCD corrections  
leads to huge  $K$ -factors  
→ apply jet veto

with jet veto  $p_{T,\text{jet}} > 100 \text{ GeV}$

- \*  $\delta_{q\gamma} < 5\%$  even in the region of high transverse momentum
- \*  $\delta_{EW} (\delta_{\bar{q}q} + \delta_{q\gamma} + \delta_{\gamma\gamma} + \delta_{\bar{b}b})$   
= -20% at  $p_T = 900 \text{ GeV}$

# LHC14: invariant mass distribution of charged leptons



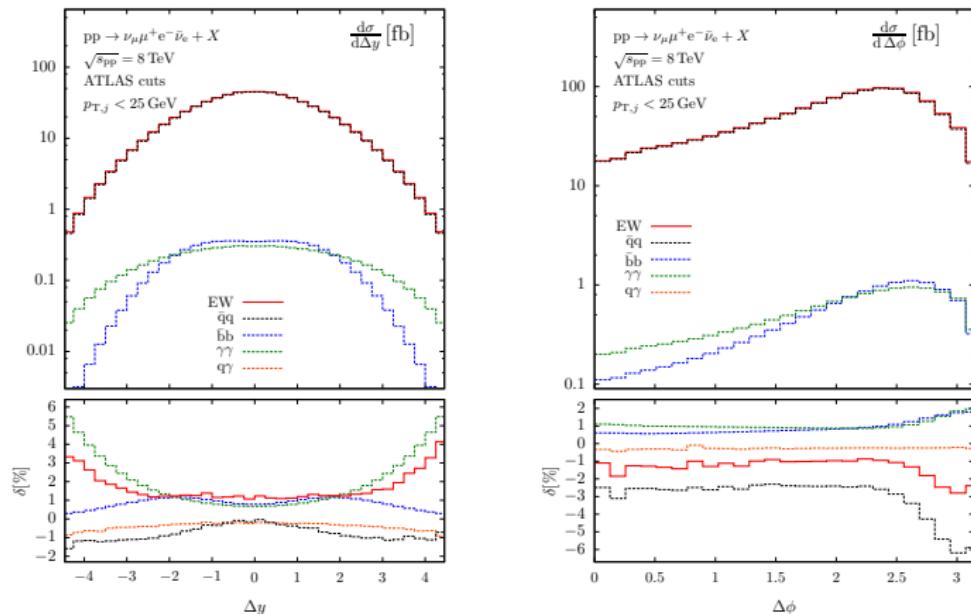
with jet veto

- \* relatively large negative EW corrections partially compensated by positive contributions, especially  $\delta_{\gamma\gamma}$

→ moderate corrections even at high invariant mass (< 10%)

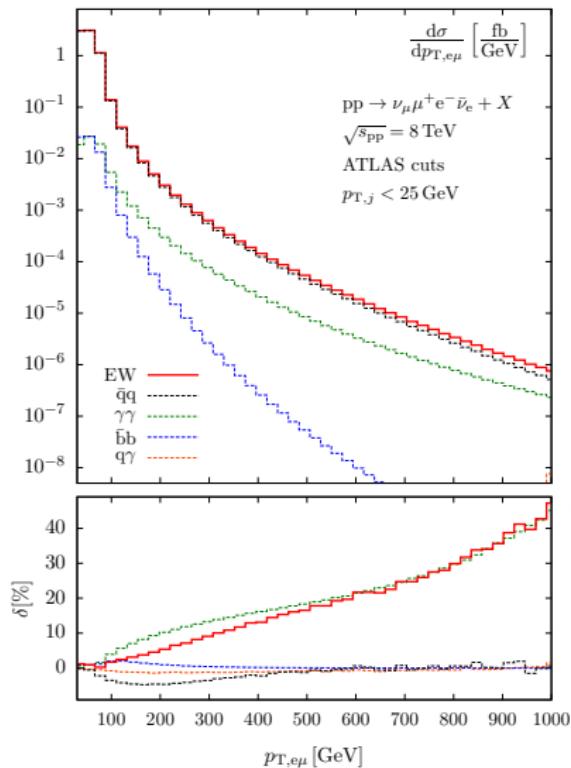
- \* same behaviour found for transverse-mass distribution  $M_{T,WW}$

# ATLAS cuts: angular distributions



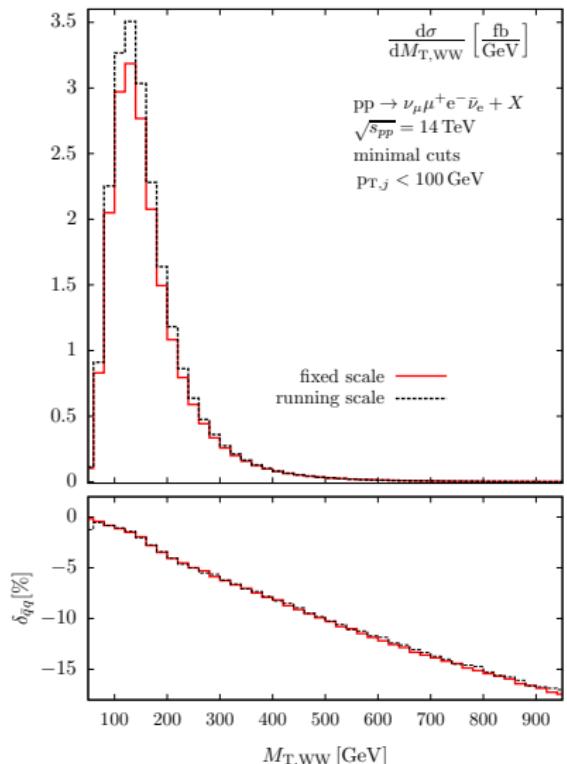
- Angular distributions in general less affected by EW corrections
- $\gamma\gamma$  contribution dominates the forward/backward emission of the charged leptons (reported by Bierweiler et al.)

# ATLAS cuts: transverse momentum $p_T(e^-\mu^+)$



- \* real radiation of **hard** photon:  
large impact by  $\text{pp} \rightarrow W^+W^-\gamma$  with  
**hard** photon
- \* large photon recoil

# LHC14: Scale dependence



- \* variation of  $\mu_F$  by a factor 2 changes the inclusive cross section by around  $\pm 8\%$
- \* but  $\delta_{\bar{q}q}$  shows no scale dependence

fixed scale  $\mu_F = M_W$ ,  
running scale  $\mu_F = M_{WW}$

→ **factorization** of EW corrections:

$$d\sigma = d\sigma_{qq}^{\text{QCD}} \times (1 + \delta_{\bar{q}q}) + d\sigma_{gg} + d\sigma_{\gamma\gamma} + d\sigma_{\gamma q}$$

$d\sigma_{qq}^{\text{QCD}}$ : state-of the-art QCD prediction

# Conclusion

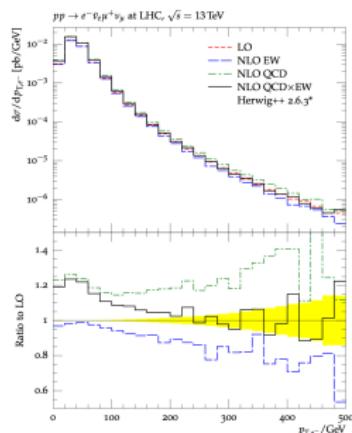
We have calculated the EW corrections to  $\nu_\mu \mu^+ e^- \bar{\nu}_e$  production at the LHC in double-pole approximation:

- ④ first evaluation of EW corrections to W-pair production with decays (realistic event selection)
- ④ previous (idealized) on-shell result confirmed within some %
  - ▶ EW corrections to integrated cross sections small
  - ▶ but sizable effects due to Sudakov logarithms in distributions at high scale
  - ▶  $\gamma\gamma$  contribution has to be taken into account
  - ▶  $\gamma q$  contribution is suppressed by jet veto
  - ▶ scale dependence low
- ④ first step towards calculation of full EW corrections to 4/ $\ell$  production

# Outlook

- ⌚ full EW corrections to  $\nu_\mu \mu^+ e^- \bar{\nu}_e$  production at the LHC  
(interesting as irreducible background to  $H \rightarrow WW^*$ )
- ⌚ inclusion of NLO QCD corrections ✓ (checked against MCFM)
- ⌚ implementation of subtraction terms for non-collinear-safe observables  
[Dittmaier, Kabelschacht, Kasprzik '08]  
→ bare leptons
- ⌚ independent check of V+E approximation

[Gieseke Kasprzik, Kühn '14]



$$d\sigma_{\text{QCD} \times \text{EW}} = K_{\text{weak}}(\hat{s}, \hat{t}) \times d\sigma_{\text{QCD}}$$

HERWIG++ provides

- ⌚ leptonic decays
- ⌚ parton shower
- ⌚ hadronization
- ⌚ FSR (SOPHTY, PHOTOS)

## Backup slides

# On-shell projection

[Denner et al.]

$$a(p_+) + b(p_-) \rightarrow f_1(k_1) + \bar{f}_2(k_2) + f_3(k_3) + \bar{f}_4(k_4)$$

- fix direction of  $W^+$  boson, of fermion  $f_1$ , and of fermion  $f_3$

$$\hat{k}_{+0} = \frac{1}{2}\sqrt{s}, \quad \mathbf{k}_+ = \frac{\mathbf{k}_+}{|\mathbf{k}_+|}\beta\frac{\sqrt{s}}{2}, \quad \hat{k}_-^\mu = p_+^\mu + p_-^\mu - \hat{k}_+^\mu,$$

$$\hat{k}_1^\mu = k_1^\mu \frac{M_W^2}{2\hat{k}_+ k_1}, \quad \hat{k}_2^\mu = \hat{k}_+^\mu - \hat{k}_1^\mu,$$

$$\hat{k}_3^\mu = k_3^\mu \frac{M_W^2}{2\hat{k}_- k_3}, \quad \hat{k}_4^\mu = \hat{k}_-^\mu - \hat{k}_3^\mu$$

with  $\beta = \sqrt{1 - 4M_W^2/s}$

$$\rightarrow \hat{k}_+^2 = \hat{k}_-^2 = M_W^2$$

## Effective collinear factor

$$f(m_q, x, E_q, \theta) =$$

$$\frac{\sin^2 \frac{\theta}{2}}{\left[ \sin^2 \frac{\theta}{2} + \frac{m_q^2 x^2}{4E_q^2(1-x)^2} \right]^2} \left\{ \sin^2 \frac{\theta}{2} + \frac{m_q^2 x^4}{4E_q^2(1-x)^2(1+(1-x)^2)} \right\}$$

where  $\theta$  is the angle between the incoming and the outgoing quark of mass  $m_q$  defined in the partonic centre-of-mass frame,  $E_q$  is the energy of the incoming quark in the same frame, and  $x = k^0/E_q$  is the fraction of the incoming quark's momentum that is carried by the emitted photon.